Journal of Forestry Research (2010) 21(4): 445–450
DOI 10.1007/s11676-010-0095-y

ORIGINAL PAPER

Fire temperature and residence time during dry season burning in a Sudanian savanna-woodland of West Africa with implication for seed germination

Sidzabda Djibril Dayamba • Patrice Savadogo • Didier Zida
Louis Sawadogo • Daniel Tiveau • Per Christer Oden

Received: 2010-01-07; Accepted: 2010-05-18

Abstract: Prescribed fire is used in the Sudanian savanna-woodland of West Africa as a forest management tool. An experiment was carried out to assess the effects of season of burning, and different vertical probe positions on maximum fire temperature and temperature residence time above 60°C which is considered lethal for plant tissues. Seasons of burning considered were: an early season fire set at the beginning of the dry season (beginning of December), mid-season fire set at the peak of the dry season (mid-January), and a late season fire at the end of the dry season (end of March). The effects of these fires on the germination of buried seeds of three socio-economically valuable tree species were also examined. Results indicated significant differences in maximum fire temperature and residence time with respect to season of burning and vertical probe position ($p < 0.001$). The highest and longest lasting temperatures were observed at 20 cm above ground during early fire and at the soil surface during mid-season and late fires. This, in turn, affected germination responses of seeds buried at different soil depths. Implications of these findings in the current management practices are discussed.

Keywords: Burkina Faso; fire season; regeneration; Savanna-woodland; tropical ecosystem

Foundation project: This work was supported by the Swedish International Development Cooperation Agency (Sida).
The online version is available at http://www.springerlink.com

Sidzabda Djibril Dayamba (✉) • Patrice Savadogo •Per Christer Oden
Swedish University of Agricultural Sciences, Faculty of Forest Sciences, Southern Swedish Forest Research Centre, Tropical Silviculture and Seed Laboratory PO Box 49, SE-230 53 Alnarp, Sweden.
Email: Djibril.Dayamba@ess.slu.se
Tel: +46 40 41 53 95; Fax +46 40 41 53 98

Patrice Savadogo
Centre National de la Recherche Scientifique et Technologique, INERA, Département Productions Forestières, 03 BP 7047, Ouagadougou 03, Burkina Faso

Didier Zida • Louis Sawadogo
Centre National de la Recherche Scientifique et Technologique, INERA, Département Productions Forestières BP 10 Koudougou, Burkina Faso

Daniel Tiveau
Centre for International Forestry Research (CIFOR) Regional Office for West Africa 06, BP 9478, Ouagadougou 06, Burkina Faso

Responsible editor: Chai Ruihai

Introduction

The use of fire for savanna management is widespread, but its effect on savanna ecosystems and especially on plant species is very much dependant on the nature of the fire regime (Nikiema 2005). In most protected Sudanian savanna-woodlands, prescribed early fire has been adopted as an ecosystem management tool to minimize the risk of severe late fire, to improve pasture production for wildlife and domestic animals, and to maintain species composition and richness (Bellefontaine et al. 2000; Sawadogo et al. 2005). Extensive data on early burning and its effects on vegetation dynamics are becoming available (Sawadogo et al. 2002; Savadogo et al. 2007; Zida et al. 2007; Savadogo et al. 2008).

However, there has been little attempt to characterize fire regimes in these ecosystems (Nikiema 2005). Prescribed early fires have been preferred to fires occurring late in the dry season because they are said to be of low intensity and less damaging for plant species. De Luis et al. (2005), however, for some species in the Mediterranean ecosystem, found a positive relationship between seedling density and fire severity. In Australia, Auld and O'Connell (1991) observed that fires of low intensity may eliminate some species from the above-ground flora. The long-term survival of such species would then depend on the longevity of seeds in the soil in relation to the chance of a future fire hot enough to stimulate germination. For some West African *Acacia*, Danthu et al. (2003) noted that for species with seeds

that do not exhibit seed coat dormancy, the response to fire is reduced to two possible behaviours: seed viability preservation or seed mortality; no stimulating effect due to scarification by fire could be observed.

Studies have revealed that fire may shape vegetation communities by differently affecting plant regeneration (Walters et al. 2004; De Luis et al. 2005). The abundance of seedlings establishing after fire may be controlled by the degree of soil heating during the passage of the fire, the distribution of seeds in the soil profile, and soil moisture availability in the postfire environment (Auld and O'Connell 1991). The time of the year at which fire occurs is an important factor determining the amount of heat released (Gillon 1983). Moreover, studies on germination response to heat shock (Herranz et al. 1998; Valbuena and Vera 2002; Zida et al. 2005) have revealed that not only the amount of heat reaching the seeds is important but also how long the seeds are exposed to a given temperature. Laboratory works allow quick and informed comprehension of such phenomenon, however as noted by Herranz et al. (1998) there could be a certain risk in using results from laboratory experiments for the interpretation of field observations.

Few works have investigated the impact of fire on the fate of seeds in the Sudanian zone (Gashaw and Michelsen 2002; Danthu et al. 2003). If predictions concerning the long term dynamics of plant species in fire-prone areas are to be made, a link between the germination - heating response of seeds across a range of plant genera and varying fire intensities that are experienced in the field is necessary (Auld and O'Connell 1991; Trollope and Trollope 2004).

This study aimed at characterizing fire temperature and temperature residence time (above 60°C) during dry season burning; and the effect of fire on the germination of seeds buried at different soil depths. The species investigated were *Detarium microcarpum* Guill. & Perr., *Entada africana* Guill. & Perr. and *Combretum glutinosum* Perr. ex DC., species that are most important as fuelwood (Sawadogo et al. 2002).

Material and Methods

Description of the study site

The study was conducted in Laba State forest which is located at 11°40’N and 2°50’W at an altitude of 300 m above sea level in Burkina Faso, West Africa. Phyto-geographically, it is situated in the Sudanian regional centre of endemism in the transition from the north to the south Sudanian Zone (White 1983). The vegetation in the study site is characterized as a tree/bush savanna with a grass layer dominated by the perennial grass *Andropogon ascinodis*, while the tree layer is dominated by Mimosaceae and Combretaceae. This vegetation is prone to annual fires during the dry season (Sawadogo et al. 2005). The unimodal rainy season lasts for about six months from May to October. Based on data collected from in situ mini-weather station, the mean annual rainfall for the period 1992-2008 was 886 ± 151 mm, and the number of rainy days per annum was 69 ± 16. Mean daily minimum and maximum temperatures ranged from 16°C to 32°C in January to 26°C–40°C in April. Soils are mainly shallow (< 45 cm depth) silty-sand and classified as Lixisols (Driessen et al. 2001).

Experimental design and burnings

A permanent experimental site, made up of 16 plots (50 × 50 m), was established in Laba forest in September 2006. The plots, located on flat ground to eliminate the influence of slope on fire behaviour (Trollope et al. 2002), were separated from each other by 20 m fire-breaks and the whole experimental site was surrounded by a 30 m wide fire-break.

The following fire treatments, each with four replicates, were randomly assigned to the 16 plots: *no fire* (control plots); *early season fire*, set at the beginning of the dry season in December; *mid-season fire*, set at the peak of the dry season in mid-January and *late season fire*, set at the end of the dry season and just before the next rainy season at the end of March. For the present study dealing with the effect of season of burning, control (unburnt) plots are naturally excluded. During early fire the open wind speed, air temperature and relative humidity were 1.3 m/s, 23°C and 27%, respectively and the corresponding values during mid-season and late fires were 3.1 m/s, 25°C, 25% and 0.8 m/s, 37°C, 30%, respectively. Fire was initiated early in the morning by igniting with a drip torch along one side of each plot at a time to rapidly establish a fire line and to ensure linear ignition. For all plots burning, and for the sake of uniformity, fire was lit following wind direction (head fires).

Recording of fire temperature and residence time

Fire temperatures were registered following the procedure described by Savadogo et al. (2007). MiniCube dataloggers with 10 thermo elements type-K and probes placed at -10, -5, -2, 0, 20, 50, 150, 300, 500 cm from ground level, were used. The particularity of the present work (as compared to previous study in the same area by Savadogo et al. (2007)) is that it includes the season of burning as a study parameter. For each burnt plot, the maximum temperature at each probe position was considered during data analysis. The series of temperatures recorded at each probe position were used to calculate the temperature residence time above 60°C which is considered lethal for plant tissues (Daniell et al. 1969). Residence time is defined as the time elapsed before the maximum fire temperature goes below 60°C.

Effect of fire on germination of buried seeds

Seed materials

Seeds of *Detarium microcarpum*, *Entada africana* (purchased from the National Tree Seed Centre and originally collected in 2002 and 1997 respectively) and *Combretum glutinosum* (collected from the Tiogo State forest, Burkina Faso (12º13' N, 2º42' W) in February 2008) were used to investigate the effects of different fire seasons on the germination of buried seeds. Seeds of *C. glutinosum* were stored for about one month while those of

the two other species, after purchase, were stored for four months at ambient conditions before the experiments. At seed centre, seeds were stored in an air conditioned room at 18-22°C and 44% RH. All studied species have no physical dormancy (Zida et al. 2005; Dayamba et al. 2008).

Treatments

Prior to burning at each fire season, seeds from the above species were buried at different soil depths (0, 2 and 5 cm), in line with the nature of the soil seed bank in the study area, which is restricted to the first few cm in the soil (Zida, pers. obs.). In each treatment plot, 60 seeds per species (enough seeds to compensate for any loss) were placed at the specified soil depths, and the batch of seeds was split into four sets and placed at different spots within each treatment plot to increase the chance of getting at least two of the sets passed by fire as well for allowing to compensate for patchy burning. Buried seeds were put in a small pit, with a bottom large enough to contain 15 seeds, covered with soil (seeds on soil surface were not covered) and the disturbed vegetation was restored. The fire treatments were applied after burial of seeds as described above and the burnt soil was left to cool for some time after the fires were extinguished. Seeds from the same species and the same soil depth in each plot were put together in one paper bag and constituted a replicate. The treated seeds were tested for germination.

Germination test

The germination trial was run for 30 days. A total of 100 seeds per species and per treatment, with 25 seeds per replicate, were sown in trays containing sterilized sand (sand heated in oven set at 120°C for two hours). For each species, untreated (unburied) seeds were also sown (4 × 25 seeds) as control. The seeds were exposed to in-coming sunlight during daytime and to darkness during the night and watered on daily basis. All other conditions (temperature) were ambient as it would naturally be in field conditions. Germination was monitored every day and a seed showing a radicle at least 2 mm long was considered as germinated, was recorded and discarded from the trays.

Statistical analysis

A two-way analysis of variance was performed to study the effects of fire regime, probe location and their interaction on fire temperature and residence time above 60°C. Homogeneity of variances was examined before the analysis using Levene's test, and heteroscedastic data were log-transformed (Gomez and Gomez 1976). The magnitude of the different effects was determined by a statistic called partial eta squared (η_p^2), and the effect was considered as small, moderate or large if the value of this statistic was 0.01, 0.06 or 0.14, respectively (Cohen 1988).

Since seeds exposed to burning during early and mid-season fires did not germinate due to unfavourable germination conditions (low temperature) in the rooms during this time of the year, germination data only from the late fire regime were reported. Conclusions are drawn for the first two fire seasons based on their fire temperatures and temperature residence time values and the germination results during late season fire. For each species and depth of burial in the soil, germination capacity (GC) and mean germination time (MGT) were calculated as:

$$GC\,(\%) = \left(\frac{\sum n_i}{N}\right) \times 100$$

$$MGT\,(days) = \frac{\sum (t_i \times n_i)}{\sum n_i}$$

where n_i is the number of seeds germinated at each day, N is total number of seeds sown and t_i is the number of days starting from the date of sowing (Bewley and Black 1994). The data set for germination capacity was arcsine-transformed to meet the normality assumption (Zar 1999). For each species, a one-way ANOVA was performed to test significant differences in germination capacity and mean germination time among depth of burial during late fire-regime. When a significant difference was detected, a pair-wise comparison was made using Tukey's test at the 5% level of significance.

Results

Fire temperature and residence time

Maximum fire temperature differed significantly with respect to fire season ($F_{2,81}$ = 16.99, p < 0.001), probe location ($F_{8,81}$ = 92.55, p < 0.001) and their interaction ($F_{16,81}$ = 3.67, p < 0.001) with large effect size in all cases (η_p^2 = 0.296, 0.901 and 0.420 for fire season, probe location and their interaction, respectively). Temperatures were significantly lower during early fire compared to mid-season and late fires (p < 0.001), but the last two fires did not differ significantly (p = 0.98). Highest temperatures were observed at 20 cm above ground during early fire and at ground level during mid-season and late fires (Fig. 1).

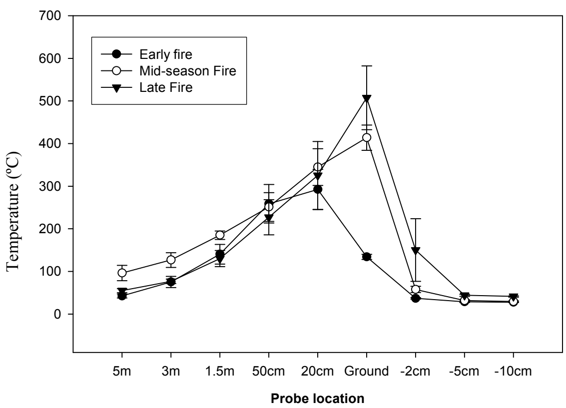

Fig. 1 Main effect of fire season on temperature values (mean ± s.e.) at different probe locations

Temperature residence time (above 60°C) was also affected by fire season ($F_{2,81}$ = 17.58, p < 0.001), probe location ($F_{8,81}$ = 27.34, p < 0.001) and their interaction ($F_{16,81}$ = 3.09, p < 0.001) with large effect size in all cases (η_p^2 = 0.303, 0.729 and 0.379 for fire season, probe location and their interaction, respectively). Early and mid-season fires did not differ significantly but, both had shorter residence times compared to late fire (p < 0.001). The residence time was longer at the soil surface than either above or below the soil surface during all three dry season fire events (Fig. 2). Also residence time in late fire was fairly similar at soil surface and 2 cm below the soil surface and was more than twice the time observed in early and mid-season fires.

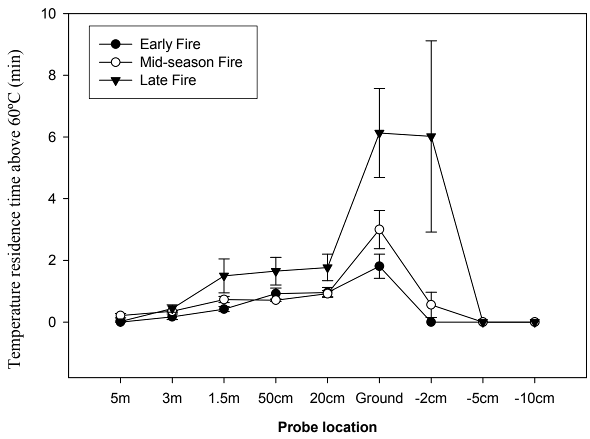

Fig. 2 Main effect of fire season on temperature residence time above 60°C (mean ± s.e.) at different probe locations

The maximum fire temperature and residence time values for the three soil depths where seeds were buried during burning are summarized as follows. At the soil surface fire temperature was 134.12 ± 5.95°C during early fire while it was more than three times during the mid-season (413.80 ± 29.37°C) and late fires (507.34 ± 74.74°C). At 2 cm below the soil surface, temperature was less than 60°C during early and mid-season fires, but was more than double (150.07 ± 73.52°C) during the late fire. Further, at 5 cm below the soil surface, temperature was less than 45°C during all fire seasons. The temperature residence time above 60°C during both early and mid-season fires was less than 3 min at the soil surface and 2 cm below the surface, while it reached 6 min during the late fire at these same soil depths. At 5 cm below the soil surface, the temperature residence time above 60°C was nil as temperature did not reach 60°C at this position.

Effect of late fire on seed germination

For all species tested, germination capacity differed significantly with respect to depth of seed burial in the soil (p < 0.001); seeds put at the soil surface during burning did not germinate at all. For the leguminous species (*D. microcarpum* and *E. africana*), there was no substantial difference between untreated seeds (control) and seeds buried at 2 and 5 cm below the soil surface during burning. For *C. glutinosum*, germination was significantly depressed in seeds buried at 2 cm below the soil surface during burning compared to untreated seeds and seeds buried at 5 cm depth (Fig. 3).

The mean germination time of the untreated seeds and seeds buried at 2 and 5 cm below the soil surface did not differ significantly in the leguminous species. On the contrary, the mean germination time of *C. glutinosum* seeds buried at 2 cm depth was doubled compared to untreated seeds (p = 0.004) and seeds buried at 5 cm below the soil surface (p = 0.002) (Table 1).

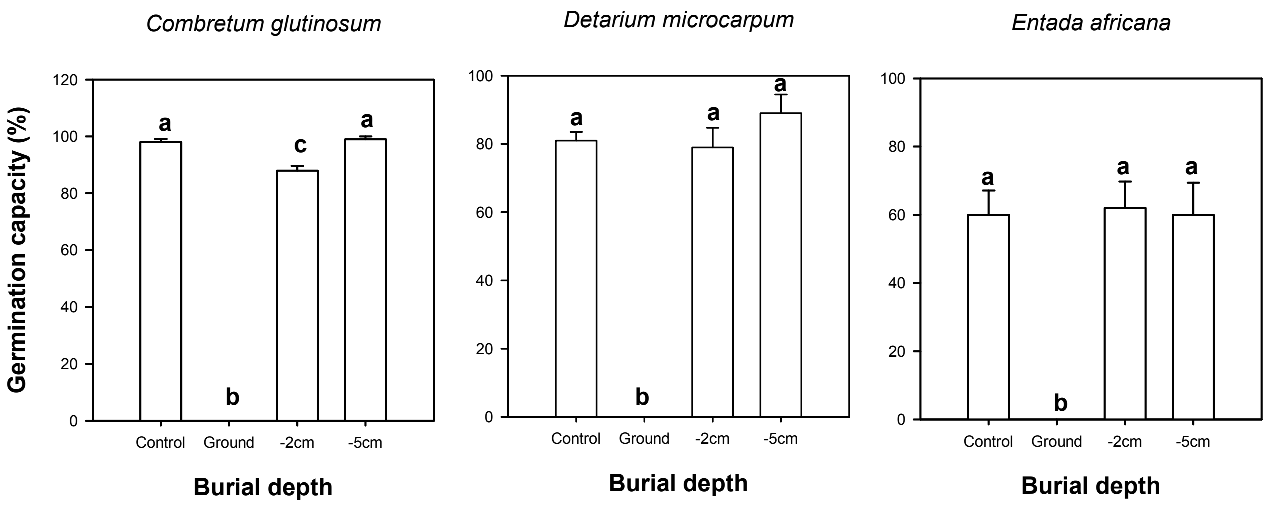

Fig. 3 Effect of depth of burial during late fire on germination capacity of tree seeds in the Sudanian savanna-woodland of West Africa. Bars with different letters are significantly different based on Tukey's HSD test.

Discussion

Higher temperatures during mid-season and late fires compared to early fire may be explained by differences in the level of desiccation of the fuel (Govender et al. 2006; Savadogo et al. 2007). Indeed, as the dry season advances, the vegetation continuously dries up as the result of long exposure to the sun. Longer residence time during late fire is explained by the fact that higher temperature would require longer time to go below 60°C compared to lower ones. Longer residence time in late fire compared to mid-season fire, despite the lack of substantial differences in temperature values, could be due to the fact that heat transfer to the atmosphere is slower during late fire when the weather is naturally warmer (Whelan 1995). The same also goes for early fire where the residence time was the lowest. As found in previous studies (Bradstock and Auld 1995; Savadogo et al. 2007), fire temperatures and residence times above the soil surface were higher than below the soil surface with a decreasing tendency with increasing soil depth. This is related to the thermal conductivity across the soil profile (Valette et al. 1994).

Table 1. Effect of late fire on mean germination time (days) of seeds buried at different soil depths

Species	Burial depth		
	Control (unburnt seeds)	2cm below ground	5cm below ground
Detarium microcarpum	24.67 ± 1.21a	27.91 ± 0.46a	26.94 ± 0.80a
Entada africana	24.29 ± 0.85a	26.20 ± 0.93a	24.61 ± 1.73a
Combretum glutinosum	9.03 ± 0.20a	17.92 ± 2.40b	7.88 ± 0.30a

Values are means ± s.e. Means followed by the same letter across the row are not significantly different (5% level) using Tukey's HSD test. As seeds placed at the soil surface (0 cm) did not germinate at all, the mean germination time is not computed

For the three species we studied, seeds placed at the soil surface did not germinate and were rotten as visually inspected at the end of the germination trial. The temperature data suggest that these seeds experienced more than 500°C during the passage of fire which certainly killed them. In an early burning experiment, Zida et al. (2007) observed that seedling density of *D. microcarpum* was substantially high on fire-protected plots compared to burnt plots, which suggests killing of seeds at the soil surface by the occurrence of extreme temperatures during their early burning. Also, an indirect fire effect such as favouring neighbouring species could have depressed seedling density of *D. microcarpum*. The substantially high temperature (150°C on average) recorded at 2 cm below ground did not make any difference in germination capacity compared to seeds in the control and 5 cm below ground in the two leguminous species. This suggests that these two species have similar temperature sensitivity and can withstand heat shock up to 150°C. Gashaw and Michelsen (2002) also reported a species from the genus *Entada*, resisting temperature of up to 200°C. The 150°C was, however, sufficient to reduce germination in *C. glutinosum*. This suggests inter-species variation in reaction to fire treatment which might be due to differences in the seeds integument's ability to protect them against high level of heat (Bond and Van Wilgen 1996). Seed length or seed mass may also account for its resistance to high temperature (Gashaw and Michelsen 2002) as embryos in large seeds (such as *D. microcarpum*) are exposed to high temperature for a shorter time period than embryos in small seeds.

As evidenced from the mean germination time, seeds of *C. glutinosum* that were not killed at 2 cm below the soil surface, took more time to germinate compared to control seeds and seeds at 5 cm below the soil surface. This suggests a need to recover from a temporary heat-induced physiological dormancy (Baskin and Baskin 1998) before germination could proceed. It could also be an adaptive strategy of timing the availability of sufficient moisture in the soil. Gashaw and Michelsen (2002) suggested that slow germination following heating of seeds in savanna fire ensures that the timing with the onset of rainy season is optimal whereas too fast germination would expose germinating seeds to drought stress before the dry season has terminated. Such trends were not observed with the leguminous species which contrast with the study by Zida et al. (2005) where increased temperature and exposure time delayed germination for *D. microcarpum* and *E. africana*. Explanation to this is that, as shown by observed residence times in this study, in real field conditions, seeds do not experience long exposure to heat shock as those (20, 40 and 60 min) tested by Zida et al. (2005).

Based on the observed temperature at the different soil depths during early and mid-season fires, and the behaviour of seeds in relation to temperatures observed during late fire, we can conclude that the proportion of seeds killed during the passage of early fire could be less at the soil surface than during mid-season and late fires; and hence fairly good germination of unburied or superficially buried seeds could occur at the surface of the forest floor. It should, however, be noted that this is restricted to the type of vegetation studied here (dominated by perennial grass), as in plots dominated by annual grass temperature can be twice as high (Savadogo et al. 2007). Since temperatures encountered during mid-season and late fires were found detrimental to the seeds (especially at soil surface), prescribed early fire could be implemented with due caution to time of burning and other factors that may increase fire severity. This is especially relevant for the studied species as seed dispersal is expected in January-February-March, just when any occurring fire would be very severe. Thus, if an early fire (which reduces available fuel load) was not set, any late coming fire would destroy the forest floor seeds of the current year and the superficially buried seeds of the previous years.

From the measurements, it is clear that successful germination is related to depth of seed in the soil profile, the type of species involved and the fire severity. Early fire, burning from October to December, would have less negative effect on germination of the studied species, irrespective of the depth of burial during fire. The present study focused on a perennial grass dominated woodland. But as shown in previous studies, the type of vegetation largely influences fire characteristics. It is therefore required that

fire season studies encompass vegetation type before large scale generalisation can be made.

Acknowledgements

Funding for this study was provided by the Swedish International Development Cooperation Agency (Sida). Thanks are due to Théophile Bama, Modeste Méda, and local people for helping in fire data gathering and for seed germination monitoring.

References

Auld TD, O'Connell MA. 1991. Predicting patterns of post-fire germination in 35 eastern Australian Fabaceae. *Australian Journal of Ecology*, **16**: 53–70.

Baskin CC, Baskin JM. 1998. *Seeds: ecology, biogeography, and evolution of dormancy and germination*. Academic Press: San Diego, California, 666 pp.

Bellefontaine R, Gaston A, Petrucci Y. 2000. *Management of natural forests of dry tropical zones*. Food and Agriculture Organisation of the United Nations Rome, Italy, 318 pp.

Bewley JD, Black M. 1994. *Seeds: Physiology of Development and Germination*. 2nd edition. New York: Plenum Press, 445 pp.

Bond WJ, Van Wilgen BW. 1996. *Fire and plants*. 1rst edition. London, United Kingdom: Chapman & Hall, 263 pp.

Bradstock RA, Auld TD. 1995. Soil temperatures during experimental bushfires in relation to fire intensity: consequences for legume germination and fire management in south-eastern Australia. *Journal of Applied Ecology*, **32**: 76–84.

Cohen J. 1988. *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Erlbaum , 567 pp.

Daniell JW, Chappell WE, Couch HB. 1969. Effect of sublethal and lethal temperatures on plant cells. *Plant Physiology*, **44**: 1684–1689.

Danthu P, Ndongo M, Diaou M, Thiam O, Sarr A, Dedhiou B, Ould Mohamed Vall A. 2003. Impact of bush fire on germination of some West African acacias. *Forest Ecology and Management*, **173**: 1–10.

Dayamba SD, Tigabu M, Sawadogo L, Oden PC. 2008. Seed germination of herbaceous and woody species of the Sudanian savanna-woodland in response to heat shock and smoke. *Forest Ecology and Management*, **256**: 462–470.

De Luis M, Raventos J, Gonzalez-Hidalgo JC. 2005. Factors controlling seedling germination after fire in Mediterranean gorse shrublands. Implications for fire prescription. *Journal of Environmental Management*, **76**: 159–166.

Driessen P, Deckers J, Spaargaren O. 2001. *Lecture notes on the major soils of the world*. Food and Agriculture Organization of the United Nations Rome, Italy, 334 pp.

Gashaw M, Michelsen A. 2002. Influence of heat shock on seed germination of plants from regularly burnt savanna woodlands and grasslands in Ethiopia. *Plant Ecology*, **159**: 83–93.

Gillon D. 1983. The fire problem in tropical savannas. In: Boulière, F. (ed.), *Tropical savannas ecosystems of the world*. Amsterdam: Elsevier, pp. 617–641.

Gomez KA, Gomez AA. 1976. *Statistical procedures for agricultural research*. New York: John Whiley & Sons, 680 pp.

Govender N, Trollope WSW, Van Wilgen BW. 2006. The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. *Journal of Applied Ecology*, **43**: 748–758.

Herranz JM, Ferrandis P, Martinez-Sánchez JJ. 1998. Influence of heat on seed germination of seven Mediterranean Leguminosae species. *Plant Ecology*, **136**: 95–103.

Nikiema A. 2005. Agroforestry parkland species diversity: uses and management in semi-arid West Africa. PhD Thesis, Wageningen University: Nertherlands, 102 pp.

Sawadogo L, Nygard R, Pallo F. 2002. Effects of livestock and prescribed fire on coppice growth after selective cutting of Sudanian savannah in Burkina Faso. *Annals of Forest Science*, **59**: 185–95.

Sawadogo L, Tiveau D, Nygård R. 2005. Influence of selective tree cutting, livestock and prescribed fire on herbaceous biomass in the savannah woodlands of Burkina Faso, West Africa. *Agriculture, Ecosystems and Environment*, **105**: 335–345.

Savadogo P, Tiveau D, Sawadogo L, Tigabu M. 2008. Herbaceous species responses to long-term effects of prescribed fire, grazing and selective tree cutting in the savanna-woodlands of West Africa. *Perspectives in Plant Ecology, Evolution and Systematics*, **10**: 179–195.

Savadogo P, Zida D, Sawadogo L, Tiveau D, Tigabu M, Oden PC. 2007. Fuel and fire characteristics in savanna-woodland of West Africa in relation to grazing and dominant grass type. *International Journal of Wildland Fire*, **16**: 531–539.

Trollope WSW, Trollope LA. 2004. Prescribed burning in African grasslands and savannas for wildlife management. Arid Lands Newsletter 55 Fire Ecology II.

Trollope WSW, Trollope LA, Hartnett DC. 2002. Fire behaviour a key factor in the fire ecology of African grasslands and savannas. In*: "Proceedings of IV International Conference on Forest Fire Research & Wildland Fire Safety"* 18-23 November 2002, Luso, Coimbra, Portugal Ed DX Viegas Millpress: Rotterdam, ISBN: 90-77017-72-0.

Valbuena L, Vera ML. 2002. The effects of thermal scarification and seed storage on germination of four heathland species. *Plant Ecology*, **161**: 137–144.

Valette JC, Gomendy V, Marechal J, Houssard C, Gillon D. 1994. Heat-transfer in the soil during very low-intensity experimental fires - the role of duff and soil-moisture content. *International Journal of Wildland Fire,* **4**: 225–237.

Walters M, Midgley JJ, Somers MJ. 2004. Effects of fire and fire intensity on the germination and establishment of *Acacia karroo*, *Acacia nilotica*, *Acacia luederitzii* and *Dichrostachys cinerea* in the field. BMC Ecology **4**, Article No. 3.

Whelan RJ. 1995. *The ecology of fire*. New York: Cambridge University Press, New York, 346 pp.

White F. 1983. The vegetation of Africa. A Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa. UNESCO: Paris.

Zar JH. 1999. *Biostatistical analysis*. Fourth Edition. Upper Saddle River: New Jersey: Prentice Hall, 662 pp.

Zida D, Sawadogo L, Tigabu M, Tiveau D, Oden PC. 2007. Dynamics of sapling population in savanna woodlands of Burkina Faso subjected to grazing, early fire and selective tree cutting for a decade. *Forest Ecology and Management*, **243**: 102–115.

Zida D, Tigabu M, Sawadogo L, Oden PC. 2005. Germination requirements of seeds of four woody species from the Sudanian savanna in Burkina Faso, West Africa. *Seed Science and Technology*, **33**: 581–593.